On the Habitabilities of Bacterial Cellulose for Living Artefacts

Groutars, Eduard; Martins, J.; Karana, E.

DOI
10.1145/3715336.3735432

Publication date
2025

Document Version
Final published version

Published in
DIS 2025 - Proceedings of the 2025 ACM Designing Interactive Systems Conference

Citation (APA)
Groutars, E., Martins, J., & Karana, E. (2025). On the Habitabilities of Bacterial Cellulose for Living Artefacts. In N. J. Nunes, V. Nisi, I. Oakley, Q. Yang, & C. Zheng (Eds.), *DIS 2025 - Proceedings of the 2025 ACM Designing Interactive Systems Conference* (pp. 1516-1529). (DIS 2025 - Proceedings of the 2025 ACM Designing Interactive Systems Conference). ACM. https://doi.org/10.1145/3715336.3735432

On the Habitabilities of Bacterial Cellulose for Living Artefacts

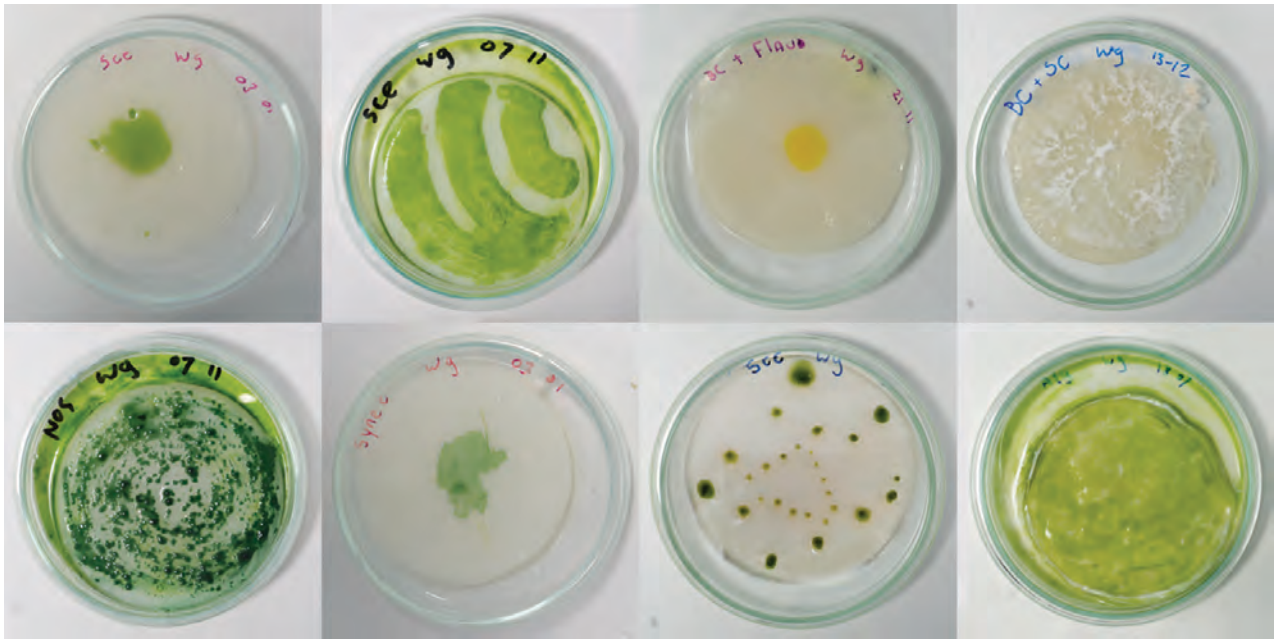
Eduard Georges Groutars
Delft University of Technology
Delft, Netherlands
e.g.groutars@tudelft.nl

Joana Martins
Delft University of Technology
Delft, Netherlands
j.martins@tudelft.nl

Elvin Karana
Delft University of Technology
Delft, Netherlands
e.karana@tudelft.nl

ABSTRACT

Bacterial cellulose (BC), also known as a Kombucha mat or SCOBY, is a grown material widely adopted in design and HCI communities due to its biodegradability, accessibility and mechanical versatility. Alongside these aspects, BC's qualities to become a habitat for other living organisms, i.e., its habitabilities, have been researched in biotechnological sciences but not fully explored in design. In response to the call for biobased material alternatives and the expanding design space for multispecies interactions in HCI, in this paper, we unpack this habitability potential of BC in the design of living artefacts. Through visual storytelling we unveil our hands-on biolab journey with *Komagataeibacter*, the bacteria that produce BC, and show how fungi, microalgae and cyanobacteria can inhabit this material. We outline diverse options for tuning the habitabilities of BC to incite HCI designers in the creation of living artefacts that are fully grown and compatible with regenerative ecologies.



DIS '25, July 5–9, 2025, Funchal, Portugal

ACM ISBN 979-8-4007-1485-6/2025/07.
https://doi.org/10.1145/3715336.3735432

Authors Keywords
Biodesign; Bio-HCI; Bacterial Cellulose; Sustainability; Regenerative Ecologies; Multispecies Interactions; Microorganisms, Living Artefacts .

CSS Concepts
Human-centered computing~ - Human Computer Interaction (HCI) - Interactive systems and tools

INTRODUCTION

In response to the escalating environmental crisis, researchers within the fields of design and HCI have increasingly explored sustainable alternatives to traditional materials and production processes (see, for an overview [33, 45]). Aligning with these developments, and responding to a broader call for ecological thinking [30] and enabling multispecies interactions [16], researchers in the fields of biodesign and biological-HCI are considering living organisms as material sources, interactive components and collaborators in the design process [21, 25, 34, 37, 43]. Within these fields, bacterial cellulose (BC) has emerged as one of the most extensively explored biodesign materials due to its accessibility and remarkable versatility (see, for example [6, 41, 47]. Among BC's diverse potentials, particularly intriguing are its habitabilities [21], i.e., the capacity of this material to provide a habitat to other living organisms. This potential of BC has been studied in biological sciences but remains largely unexplored within design communities. In this work, we explore the habitabilities of BC, positioning it as a promising bio-based alternative for the design of living artefacts that are fully grown, biodegradable and able to host a diverse array of microorganisms in diverse contexts.

RELATED WORK

Bacterial Cellulose in Biotechnological Sciences

Bacterial cellulose (BC) is a biomaterial grown by several bacteria (famous examples include *Acetobacter xylinium* and *Komagaeteibacter hansenii*) which are for example found in Kombucha, a fermented tea beverage. During the fermentation process, bacteria secrete cellulose chains that form a biofilm at the air-water interface of a liquid culture (see figure 2). This biofilm, which is also referred to as a BC pellicle or a SCOBY (Symbiotic Culture Of Bacteria and Yeast), consists of pure, nano-scale cellulose fibers, giving the material unique mechanical properties such as a high strength and stiffness [14, 19]. Scientists have suggested that the reason for these bacteria to produce cellulose is to create an extra-cellular habitat that provides them with protection from UV radiation, chemicals and optimises access to nutrients and oxygen [19]. Expanding on this notion of BC being a habitat created by microorganisms, studies have also shown it to be a suitable habitat for other microorganisms, highlighting the excellent biocompatibility and bioreceptivity of this material due to its porosity, permeability and liquid holding capacity [8, 49]. BC has therefore seen usage as a base material for the development of engineered living materials [39] where for example photosynthetic microalgae [4], yeast cells [13], bacteria [29] and complex living assemblages [22] are grown both on and into BC. Building on this ongoing work, we foresee a rich yet underexplored design space for BC based living artefacts that are able to host a variety of living organisms, enabling cohabitation and multispecies interactions in the everyday.

Bacterial Cellulose in Design and HCI

In 2000, Suzanne Lee used BC to grow fashion garments [26], which since then has been followed by numerous explorations in design [10, 47] and led to the development of startups growing BC based textiles [31, 35]. In HCI, BC has been explored as a material for interactive interfaces [38, 40], pointing towards the benefits of this material as a sustainably produced and biodegradable alternative for housing of electronic systems. Bell et al. [6] used BC to grow an interactive wearable with embedded electronics over the course of 13 weeks, adopting a slow paced and intimate way of making in collaboration with another organism. Alongside this are other projects involving BC as a growable biobased material in which researchers highlight the intricacies of designing with living matter [1, 7, 41]. Contributing to this body of work, we present the rich design space that BC offers as a medium for creating living artefacts.

Bacterial Cellulose as a Living Artefact

Living artefacts, as described by Karana et al. [21], are artefacts in which the livingness of an organism is prolonged during both the design and use time of an artefact. In their framework, they propose three fundamental pillars, living aesthetics, habitabilities and mutualistic care that underpin the design of living artefacts. Here the concept of habitabilities, i.e., the ability of living and non-living entities (in our case, BC) to provide a habitat and condition the livingness of organisms [21], provides a useful lens for exploring the potentials of BC, pertaining not only to ''understanding and embodying the habitat during design time but also perpetuating this habitat during both design and use time of an artefact'' [52]. Given the apparent potential of BC to provide a habitat to a variety of living organisms, we view BC as an excellent yet underexplored material platform for the design of living artefacts. Firstly because it can offer a biobased alternative to many of the synthetic materials (such as glass, plastics and metals) conventionally used in microbiology, enabling the creation of fully grown and biodegradable living artefacts. Secondly, with its capacity to serve as a habitat for many different species of microorganisms, BC offers a platform for dynamic multispecies interactions [16], opening up opportunities for cohabitation and collaboration in both laboratory settings and everyday ecosystems.

Therefore, the biodegradability and habitability of BC motivate us to further explore its potential in designing living artefacts for regenerative ecologies [23]. BC-based living artefacts, which enable cyclical material and energy flows whilst supporting multispecies interactions, hold the potential to contribute to ecosystems. These artefacts may function as autopoietic systems—where all constituent members collaboratively engage in the creation, transformation, and ongoing evolution of shared habitats [23]. To support such future explorations in design and HCI, we must first identify viable processes and provide a design space that leverages BC's potential as a habitat for living microorganisms.

OUR APPROACH

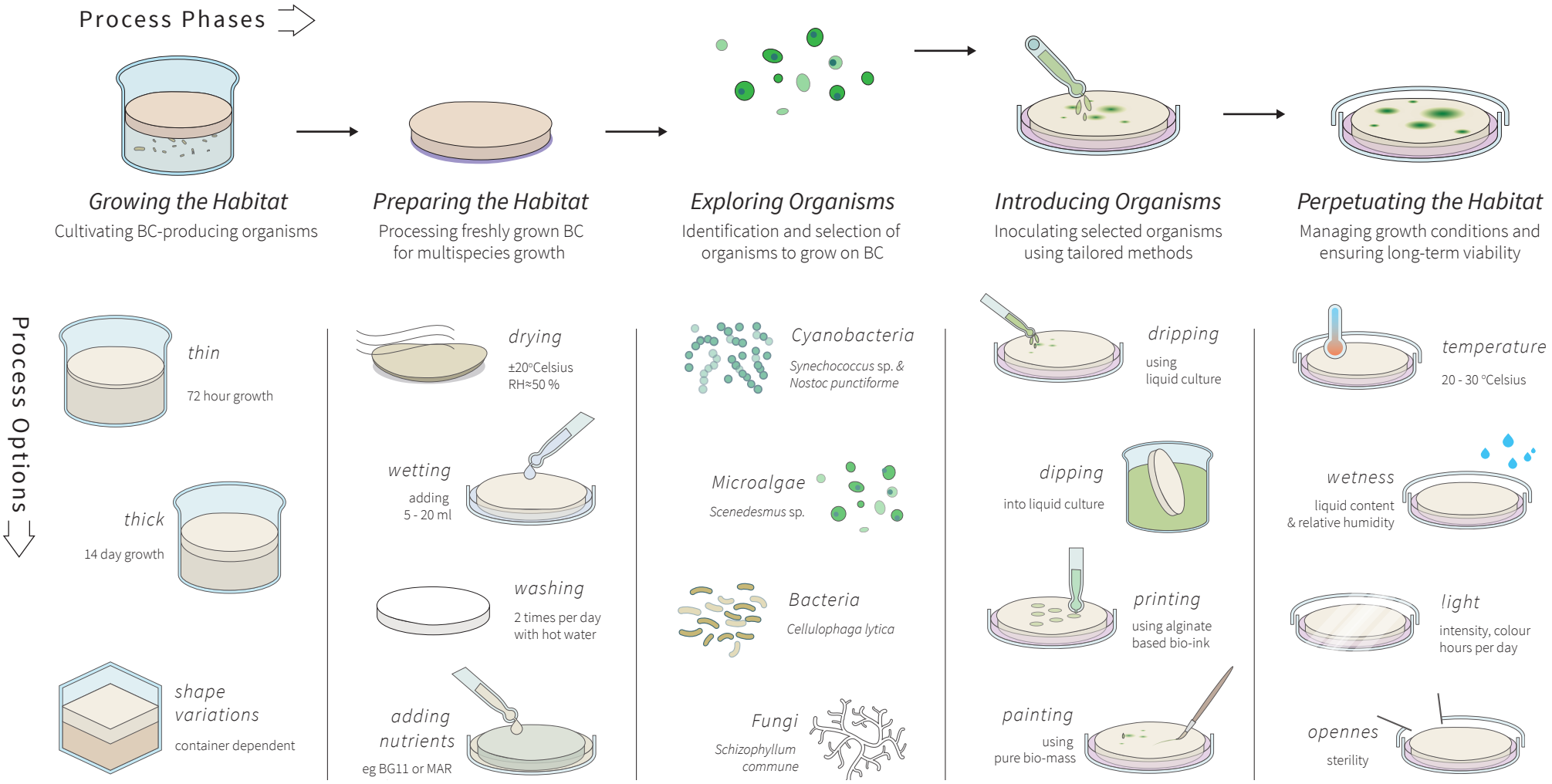
Komagataeibacter hansenii growing in the laboratory

We explored the habitabilities of bacterial cellulose (BC) by adopting a cross-disciplinary approach, combining microbiological protocols for growing [11], treating [44] and inoculating BC [4], with techniques adopted from the material driven design method including the creation of a material-process diagram and systematic tinkering, [20]. Here the process of tinkering [42] with the material allowed for fast iterations and a broad exploration of different methods with which BC can be developed into a living artefact.

Informed by our lab explorations, we defined a design space consisting of five process phases required for creating a living artefact out of BC. For each of these process phases, we identify a number of process options and discuss how these can be leveraged to influence the habitabilities of the material. Our expertise in biodesign and complementary backgrounds in interaction design, design engineering (first and third authors), and microbiology (second author), enabled us to bridge design explorations with microbiological techniques. We describe biotechnical details as well as designerly qualities in our imagery to promote flexibility in thinking across them. Whilst we do provide the technical details sufficient to replicate our explorations, our work does not adhere to strict biological protocols; instead, it represents an initial and organic overview of a design space that is meant to evolve and expand. We believe this approach will serve as a valuable inspiration for other designers, encouraging them to embark on similar explorations and contribute to this growing field.

Throughout this process of balancing design and microbiology, working with *Komagataeibacter hansenii* and the material that these bacteria produce, we continuously questioned the nature of our collaboration with this organism and the inherent tensions and dilemmas we encountered. See also our ‘Reflections and Future Work’ section.

DESIGN SPACE



Process phases

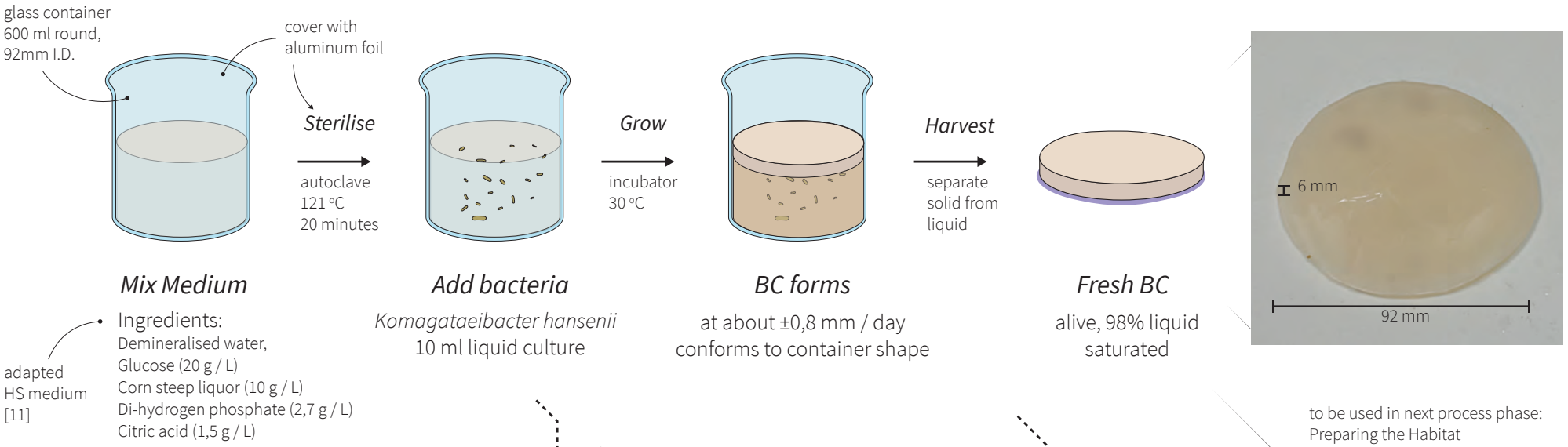
In this overview, we outline the process of developing and perpetuating BC-based living artefacts in five key phases. It is important to note that this process is not necessarily linear, nor are the steps always distinct (see for example Gilbert et al. [13], where the first and fourth step are combined) . This stepwise division primarily serves to structure our exploration and provide insights into the possibilities for tuning the habitabilities of BC.

Process options

With each process phase, different parameters can be varied as illustrated in the overview above. The decisions made at each stage will directly impact the habitabilities of the resulting living artefact. While the options presented are not exhaustive, they highlight the broad spectrum of possibilities for tuning the habitabilities of BC.

In the sections that follow, we share our lab explorations within this design space.

GROWING THE HABITAT



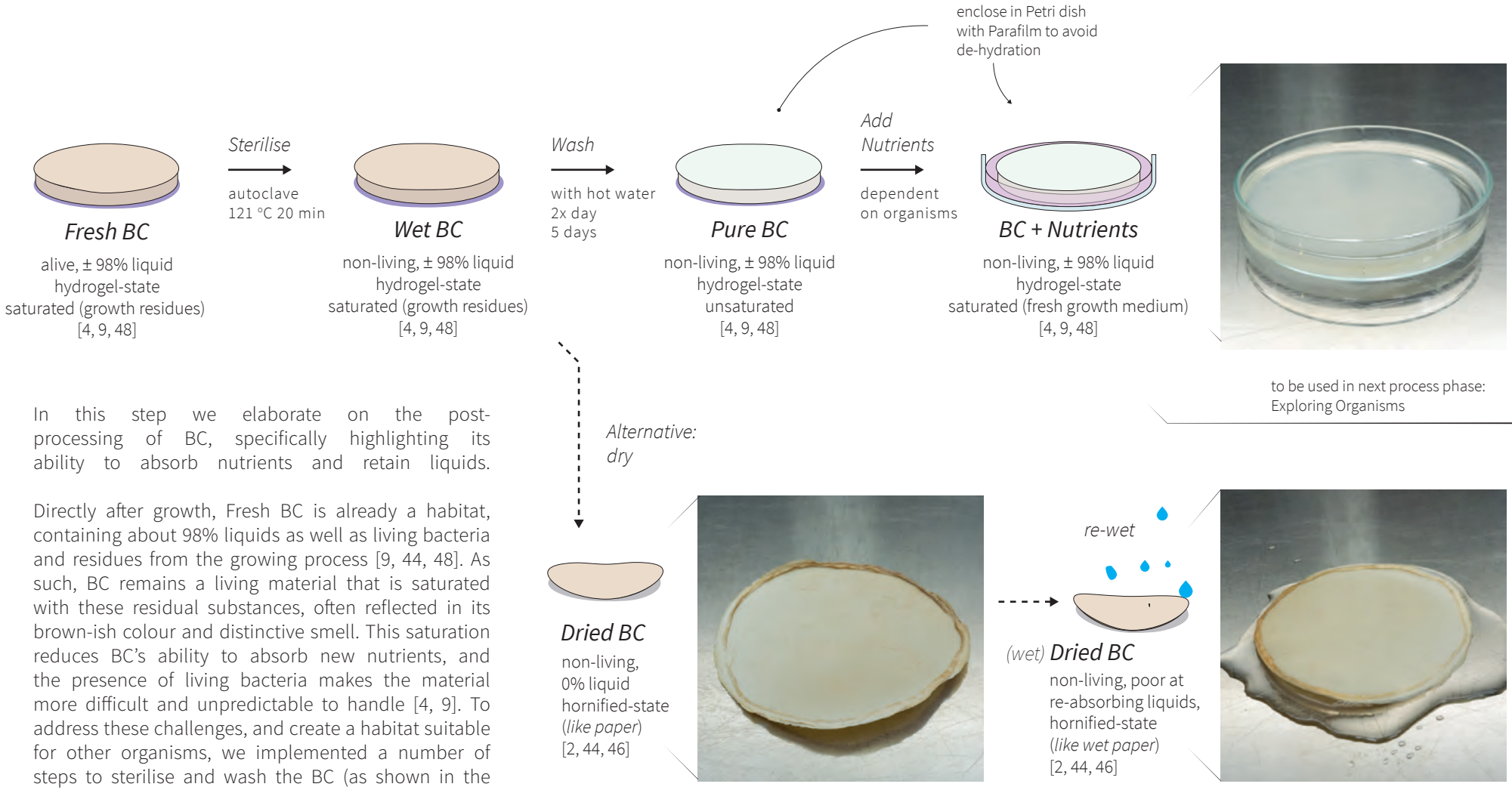
Bacterial cellulose (BC) can be grown using a range of bacterial species, from well characterized model organisms like *Komagataeibacter hansenii* [27] to complex microbial communities found in Kombucha cultures [32]. Additionally, different nutrient sources can be used, which, along with the selected BC-producing organism, will affect the yield and properties such as the density and smell of the material [11. 36]. Additionally, during growth, BC can be formed into various shapes and sizes, depending on the container's shape and the growth duration. Designers and researchers have also experimented with growing BC into 3D forms using silicone based moulds or aerated media [3, 54]. These approaches open up exciting possibilities for customising the habitabilities and design applications of bacterial cellulose.

In our approach, we adopted a standardized way of growing bacterial cellulose, as depicted above. This process yielded a consistent shape, size and composition of BC that fitted into a Petri dish, enabling us to compare different options for tuning the habitabilities and introducing microorganisms in subsequent stages.

Alternatives to this process did, however, present themselves. We experimented with growing BC into alternative shapes by varying the growth container. Also, when BC was grown for longer periods of time, its thickness increased, provided that sufficient nutrients were available to sustain prolonged growth.

This increase in thickness will impact the habitabilities of BC, as thicker material can retain more liquid and nutrients. Additionally, increased thickness can provide more shading from light sources which can be both beneficial and disadvantageous, depending on the specific organism inhabiting BC.

PREPARING THE HABITAT



In this step we elaborate on the post-processing of BC, specifically highlighting its ability to absorb nutrients and retain liquids.

Directly after growth, Fresh BC is already a habitat, containing about 98% liquids as well as living bacteria and residues from the growing process [9, 44, 48]. As such, BC remains a living material that is saturated with these residual substances, often reflected in its brown-ish colour and distinctive smell. This saturation reduces BC's ability to absorb new nutrients, and the presence of living bacteria makes the material more difficult and unpredictable to handle [4, 9]. To address these challenges, and create a habitat suitable for other organisms, we implemented a number of steps to sterilise and wash the BC (as shown in the image). These steps, effectively killing and removing Komagataeibacter hansenii from the habitat they created, conflicted with some of our personal motives but were also essential in enabling further processes (see also our 'Reflections and Future Work' section).

This resulted in Pure BC that was odourless, white of colour and able to absorb new liquids, such as different nutrient media, alllowing other microorganisms to grow [4].

Another important aspect is the liquid content of BC. Fresh BC is at a hydrogel-state, permeable and containing 98% liquids. When BC is left to dry by evaporation at room temperature, its microstructure collapses in an irreversible process called hornification [46]. The resulting Dried BC will be decreased to about 2% of its original thickness and will lose its porosity, thus significantly diminishing its ability to re-absorb liquids [2].

Once fully dried, BC takes on a paper-like appearance and texture and has decreased habitabilities, as it will no longer be able to provide the moist environment and nutrients required by the majority of living organisms. Therefore, in our explorations, we chose to keep BC hydrated either by submerging it in liquid or by enclosing it in a Petri dish sealed with parafilm.

EXPLORING ORGANISMS

Add microorganisms

By pipetting 1 ml of liquid culture

BC + Nutrients

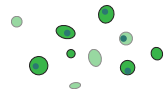
10 ml of BG11 for Microalgae
10 ml of BG11 for Cyanobacteria
10 ml of MAR for Bacteria
no additional nutrients for Fungi

We explore the growth of diverse microorganisms on BC. We have included organisms from distinct domains of life, ranging from simpler cells (e.g., bacteria and cyanobacteria) to more complex ones (e.g., microalgae and fungi), in an attempt to simulate the complexity of natural ecosystems. During our explorations, these different organisms successfully grew on BC, provided the habitabilities were tuned based on the specific conditions required for each microorganism.

To facilitate this, we added organism specific nutrient media to the BC [12, 15], inoculated the material by pipetting a liquid culture of microorganisms, and incubated them following organism specific protocols to ensure optimal conditions for each organism. Note that we will discuss variations in inoculation and incubation methods in the next section, as well as how these factors influence the habitabilities of BC.

It is important to note that while the habitat was tuned for the organisms initially, the addition of an organism will further alter the BC over time. Additionally selecting a specific organism will influence the habitability of BC for other organisms as time progresses. Much like in natural ecosystems, certain organisms may dominate or modify a habitat, limiting the habitabilities for other organisms, and potentially for themselves. Careful consideration when exploring and selecting a species is thus crucial.

microalgae used in next phase:
Introducing Organisms



Microalgae

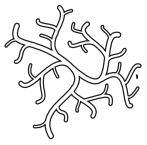
Scenedesmus sp.
incubate at 20 °C
light conditions [12]

Cyanobacteria

Synechococcus sp.
incubate at 20 °C
light conditions [12]

Bacteria

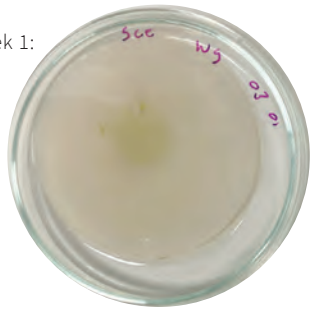
Cellulophaga lytica
incubate at 20 °C
dark conditions [15]



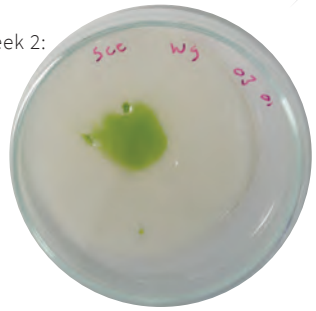
Fungi

Schizophyllum commune
incubate at 30 °C
dark conditions

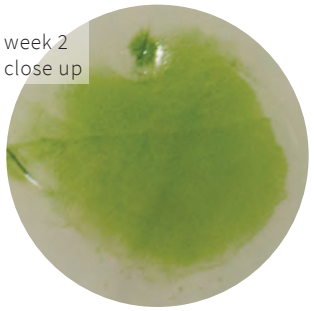
week 1:



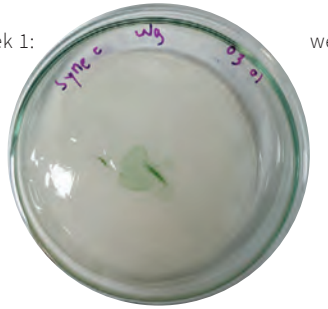
week 2:



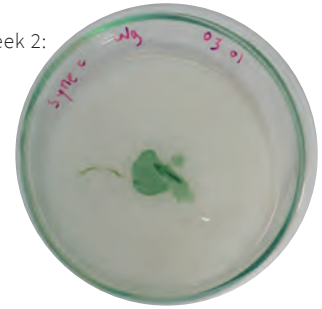
week 2 close up



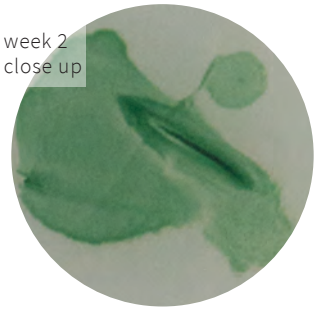
week 1:



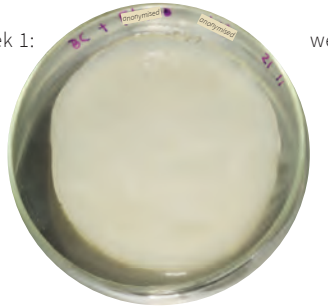
week 2:



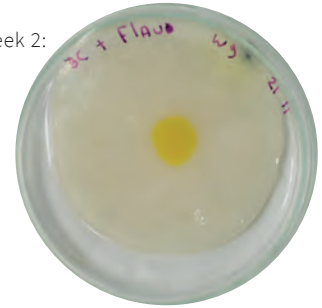
week 2 close up



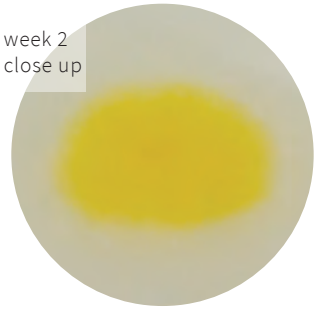
week 1:



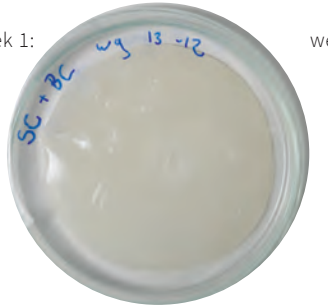
week 2:



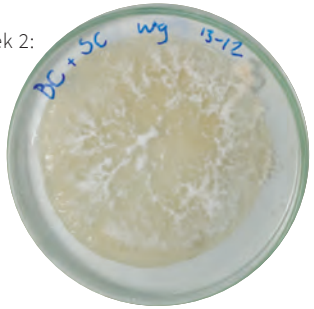
week 2 close up



week 1:



week 2:



week 2 close up

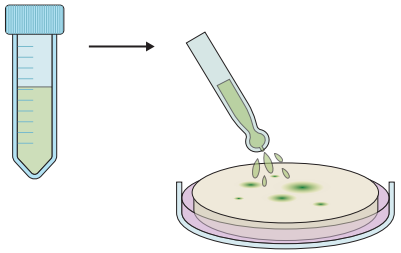
INTRODUCING MICROORGANISMS

Various methods can be used to introduce living microorganisms to the surface of BC. In this study, we explored different approaches, drawing inspiration from standard inoculation techniques in microbiology, while also incorporating more creative approaches. To compare these techniques, we opted to focus on the microalgae *Scenedesmus* sp. as it is relatively straightforward to cultivate and its growth is highly visible, making it an accessible and practical choice for biodesign explorations. Each method renders different forms, textures, and changes over time, i.e. living aesthetics [21].

Dripping a liquid culture of the selected organism(s) directly onto the surface of BC, like applied on the previous page, was a simple and straightforward technique. However, this method provided little control over where the organism(s) began to grow. Particularly with larger volumes, the organism(s) tended to float on the surface before settling in.

Printing using an alginate-based bio-ink allowed for more precise spatial distribution of growth. During our explorations this was done by hand but especially when this technique is combined with a converted 3D printer [4] this can allow for more refined patterns of growth. Additionally, adding nutrients to the bio-ink ensures that organisms have access to essential resources, in addition to those already available in the BC.

Dipping BC into liquid cultures of microalgae and letting them sit for 7 days was another method we tested. This technique led to a significant aggregation of microalgae cells onto the surface. When taken out of the liquid, the resulting BC exhibited an evenly distributed microalgae coverage. (It's worth noting that this method also integrates a step from the previous 'Preparing the Habitat' phase).

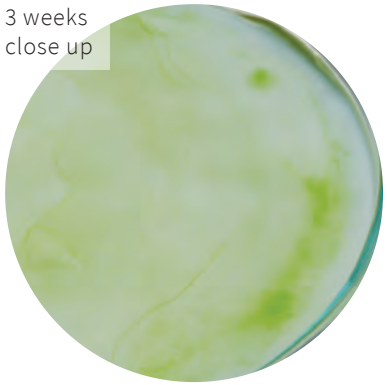


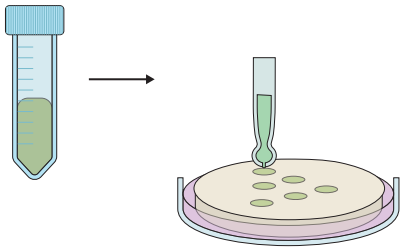
Dripping

Drip 5 ml of *Scenedesmus* sp. liquid culture
onto BC saturated with BG11 medium
incubate at 20 °C and light conditions [12]

1 week:

3 weeks
close up

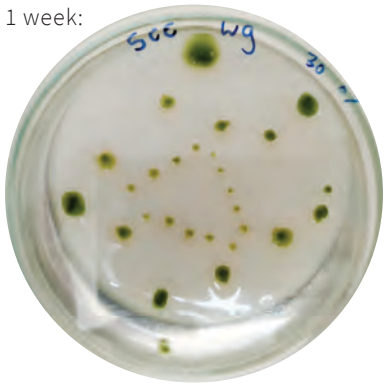




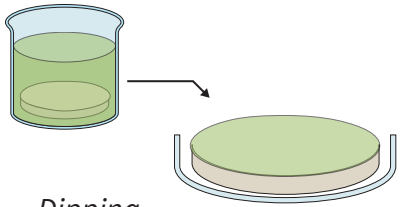
Printing

Deposit 2 ml of bio-ink by hand
(bio-ink = *Scenedesmus* sp. *cells*,
50% BG11 medium and 2,5% alginate [4])
onto BC treated with Ca^{+} ions
incubate at 20 °C and light conditions [12]

1 week:



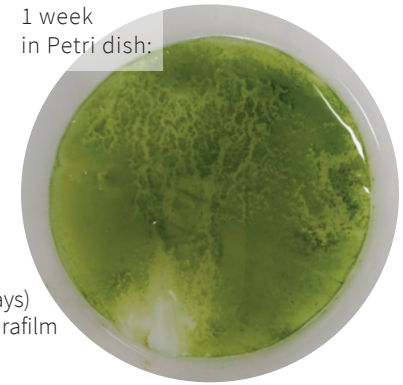
3 weeks
close up



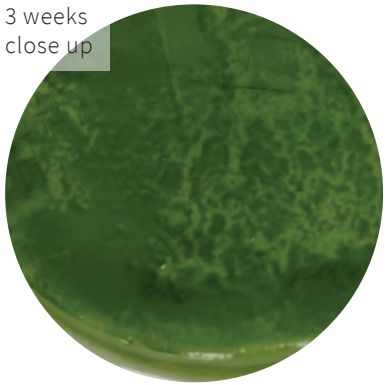
Dipping

Dip pure BC into 200 ml of
Scenedesmus sp. liquid culture
incubate at 20 °C and light conditions (7 days)
take BC out place in Petri dish, seal with parafilm
incubate at 20 °C and light conditions [12]

1 week
in Petri dish:

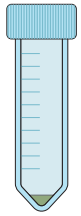


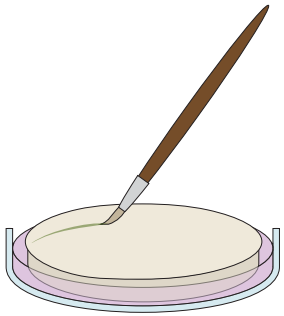
3 weeks
close up



Bio-paint

Scenedesmus sp.
Pure cell mass, centrifuged
(4000 rpm for 5 minutes)

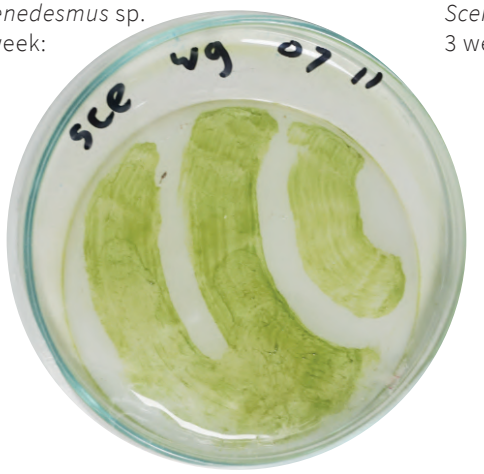




Painting

Apply directly
using sterilised brush
incubate at 20 °C and
light conditions [12]

Scenedesmus sp.
1 week:



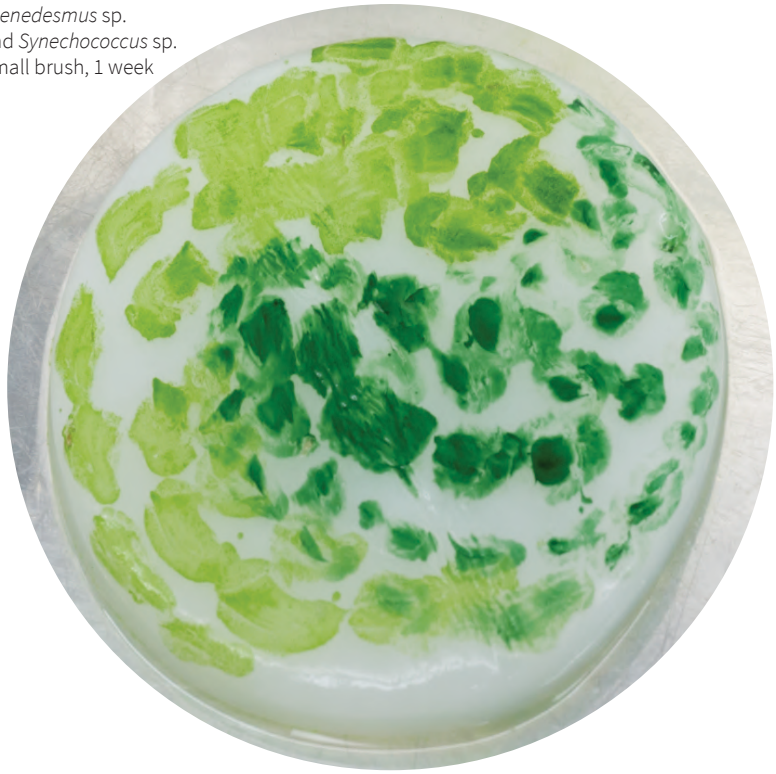
Scenedesmus sp.
3 weeks:

Painting cells directly onto the surface of BC provided further tuning where microalgae growth would start. Additionally, the hairs of the brush also slightly dented the BC surface, creating small grooves in the surface where the cells could aggregate. In this way, the habitat could be tuned through the movements of the human hand.

Much like a painter using different types of paint on a canvas, this technique prompted us to start combining organisms onto BC. Here, organisms that require similar habitabilities (like cyanobacteria and microalgae, that both grow on BG11), could be applied to the same habitat, creating a more diverse environment.

Alternative:
Painting with
multiple species

Scenedesmus sp.
and *Synechococcus* sp.
Small brush, 1 week



Scenedesmus sp.
and Nostoc punctiforme
big brush, 3 weeks

Close up of *Scenedesmus* sp.
and *Synechococcus sp.*
small brush, 1 week

PERPETUATING THE HABITAT

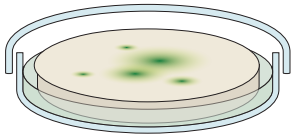
After introducing the microorganisms, BC effectively becomes a living artefact [21]. Situating living artefacts in everyday contexts requires considerations on how to perpetuate habitabilities. These do not only involve considerations on what the optimal conditions are for the artefact to thrive, but also how living artefacts might respond to fluctuations in growth conditions, which inherently occur in everyday contexts.

In our previous explorations, living materials were incubated in Petri dishes sealed with parafilm to maintain the right humidity, along with temperature and light conditions informed by organism specific protocols. These 'optimal' conditions allow us to perpetuate the habitat, ensuring livingness for longer periods of time. However, we were also interested in what would happen when these living artefacts are subjected to 'inadequate' conditions, such as drought.

For that, a 58 day old living artefact was subjected to dry sterile air, which effectively caused the BC to lose its liquid contents and shrink in size (as described in the 'Preparing the Habitat' section). Interestingly, these dried materials could be revived by adding a fresh nutrient medium, prompting microalgae to regrow. This demonstrates BC-based living artefacts' resilience to humidity fluctuations, highlighting their potential for enduring real-life conditions. Exploring ways to perpetuate BC's habitability in real-life settings is an exciting avenue for future research.

Additional: validate livingness

Re-suspend cells in BG11 to check for growth

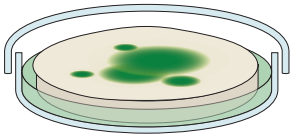


Living artefact

BC with BG11 and *Scenedesmus* sp. (dripped)

Perpetuate →

incubate at 20 °C and light conditions [12]

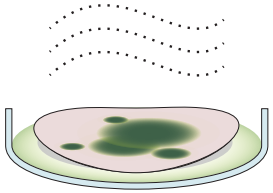


Living artefact

BC with BG11 and *Scenedesmus* sp. (dripped)

Dry →

Using sterile (HEPA filtered) air flow

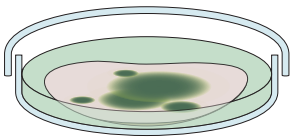


Dried artefact

BC (hornified) with BG11 residue *Scenedesmus* sp. (alive?)

Revive →

Add 10 ml of BG11 incubate at 20 °C and light conditions [12]

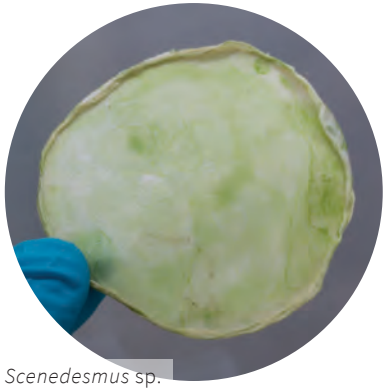


Revived artefact

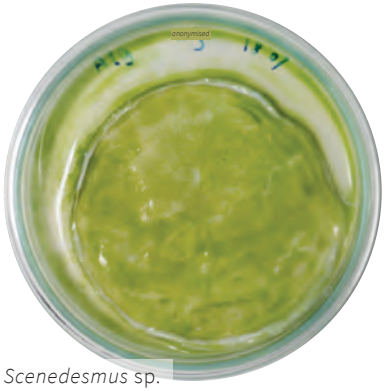
BC (hornified) with new BG11 living *Scenedesmus* sp. cells

Scenedesmus sp.
7 days old:
(dripped sample also shown in 'Introducing Organisms' section)

Scenedesmus sp.
58 days old



Scenedesmus sp.
65 days old



Scenedesmus sp.
105 days old

REFLECTIONS AND FUTURE WORK

Through our journey with bacterial cellulose (BC) and the microorganisms that produce and can inhabit it, we uncovered a rich and versatile design space, highlighting the potential of BC as a material platform for living artefacts. This versatility is particularly evident in the different species able to inhabit BC given that its habitabilities are correctly tuned, for example, by managing liquid contents and nutrient saturation of the material. Combined with its mechanical stability and biodegradability, we therefore view BC as a promising biodesign material that can serve as a habitat for a wide range of organisms and provide versatile application contexts for HCI designs. In this section, we will briefly unpack this potential further, in particular discussing implications for our future work on multispecies interactions [16] and surfacing livingness [25] in the everyday.

Bacterial Cellulose for Surfacing Multispecies Interactions

The botanist and microbiologist Baas Becking famously stated: "*everything is everywhere, but the environment selects*" [5, 51], relating to the remarkable dispersal potential of microorganisms given that the environment provides the right habitabilities. Based on our lab explorations, we can state that bacterial cellulose is able to provide such habitabilities, supporting the interconnected and rich diversity of life found in ecological systems. Here we envision a range of BC-based artefacts that are shaped and tuned to invite living organisms to inhabit the material, effectively becoming a living artefact, through interactions with their environment. As such, BC can provide a canvas to surface the livingness of other-than-humans [25], revealing temporal scales and interaction dynamics that are otherwise concealed from human perception. Creating this room for noticing [28] and subsequent interpretation is deemed an important first step in extending the traditional interaction paradigm beyond the human-computer interface to encompass ecological interactions [16, 30, 50].

An impression of our ongoing explorations to perpetuate the habitabilities of BC in real-life settings

However, exploring BC's potential role in ecological contexts necessitates careful consideration of issues such as control, safety, and more-than-human ethics, all of which are critical for the responsible advancement of this field. Introducing new organisms—or, as in our case, new materials—into existing ecosystems demands not only a thorough understanding of ongoing ecological processes but also careful consideration of potential environmental impacts, long-term viability, ethical and legal implications.

In addition to consulting experts in the involved fields, such as biology, ecology and bioethics, we propose that designers adopt an iterative approach, wherein controlled experiments conducted in the lab inform cautious and deliberate interventions in external environments, and vice versa. As such, we foresee a role for HCI designers to bridge scientific fields, interchange ways of working and engage with multispecies interactions in the wild.

Navigating Sustainability with and through Living Artefacts

Finding ecologically conscious material alternatives can be particularly challenging in the design of living artefacts due to the unfamiliarity and complexity involved with working with living organisms. Therefore, biodesigners often use existing material solutions to demonstrate proof of principles in living artefacts [15, 52] while adhering to laboratory standards. As a result, sustainable alternative solutions for living artefacts are frequently framed as future goals rather than immediate, practical implementations. We showed the ability of bacterial cellulose (BC) to host diverse living organisms, holding potential to create a new generation of fully grown living artefacts. We hope our work will encourage HCI designers to expand on such explorations, within and beyond BC. We understand that sustainability extends beyond mere material choices. Yet, within the realm of biodesign, thoughtful material decisions hold the power to weave into the cycles of life, creating compostable living artefacts that return to the earth as nourishment, sustaining and feeding the systems they emerge from.

Personal Reflections from a Design Researcher

Coming from a design background, I feel privileged to have the opportunity to collaborate with microbiology experts and a diverse host of microorganisms. Yet I am also conflicted about the nature of some of these collaborations, especially with Komagataeibacter hansenii, an organism I have propagated and nourished but also extracted and killed extensively. Here the livingness of this organism often made way for that of another and microbiological methods, in which we attempt to control experimental outcomes, have until now, prevented me from investigating possibilities of reciprocity and cohabitation between organisms. Here, requirements for control and accuracy, with which one is supposed to depict experiments, also conflicted with what originally drove me to perform them: a fascination with living aesthetics and the inherent messiness that they emerge from. I believe these tensions should guide us as biodesigners in traversing the liminal spaces between laboratories and the boundless ecosystems that lie beyond.

ACKNOWLEDGEMENTS

We thank the members of the Center of Design Research for Regenerative Material Ecologies for their feedback and support.

This research is supported by the NextSkins project, funded by the European Union's Horizon Europe Research and Innovation Programme under grant agreement number 101071159.

REFERENCES

[1] Mirela Alistar and Margherita Pevere. 2020. Semina Aeternitatis: Using bacteria for tangible interaction with data. In Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3334480.3381817

[2] Verena Andree, Daniel Niopek, Christine Müller, Jan-Philipp Eiselt, Nina Foh, Alexander Rzany, and Bernhard Hensel. 2021. Influence of drying methods on the physical properties of bacterial nanocellulose. Materials Research Express 8, 2: 025402. https://doi.org/10.1088/2053-1591/abe016

[3] Henrik Bäckdahl, Bo Risberg, and Paul Gatenholm. 2011. Observations on bacterial cellulose tube formation for application as vascular graft. Materials Science and Engineering: C 31, 1: 14–21. https://doi.org/10.1016/j.msec.2010.07.010

[4] Srikkanth Balasubramanian, Kui Yu, Anne S. Meyer, Elvin Karana, and Marie-Eve Aubin-Tam. 2021. Bioprinting of Regenerative Photosynthetic Living Materials. Advanced Functional Materials 31, 31. https://doi.org/10.1002/adfm.202011162

[5] L.B. Becking. 1934. Geobiologie of inleiding tot de milieukunde. WP van Stockum & Zoon.

[6] Fiona Bell, Derrek Chow, Hyelin Choi, and Mirela Alistar. 2023. SCOBY BREASTPLATE: SLOWLY GROWING A MICROBIAL INTERFACE. In Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction, 1–15. https://doi.org/10.1145/3569009.3572805

[7] Fiona Bell, Joshua Coffie, and Mirela Alistar. 2024. Bio-Digital Calendar: Attuning to Nonhuman Temporalities for Multispecies Understanding. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction, 1–15. https://doi.org/10.1145/3623509.3633386

[8] Joaquin Caro-Astorga, Kenneth T. Walker, Natalia Herrera, Koon-Yang Lee, and Tom Ellis. 2021. Bacterial cellulose spheroids as building blocks for 3D and patterned living materials and for regeneration. Nature Communications 12, 1: 5027. https://doi.org/10.1038/s41467-021-25350-8

[9] Wen-Shuo Chang and Hui-Huang Chen. 2016. Physical properties of bacterial cellulose composites for wound dressings. Food Hydrocolloids 53: 75–83. https://doi.org/10.1016/j.foodhyd.2014.12.009

[10] Nitzan Cohen, Emma Sicher, and Seçil Uğur Yavuz. 2022. From Agricultural Waste to Microbial Growth and (G)Local Resilience. . 81–92. https://doi.org/10.1007/978-3-030-86596-2_7

[11] Andrea F. S. Costa, Fabíola C. G. Almeida, Glória M. Vinhas, and Leonie A. Sarubbo. 2017. Production of Bacterial Cellulose by Gluconacetobacter hansenii Using Corn Steep Liquor As Nutrient Sources. Frontiers in Microbiology 8. https://doi.org/10.3389/fmicb.2017.02027

REFERENCES

[12] Amrita Difusa, Jayanta Talukdar, Mohan Chandra Kalita, K. Mohanty, and Vaibhav V. Goud. 2015. Effect of light intensity and pH condition on the growth, biomass and lipid content of microalgae Scenedesmus species. Biofuels 6, 1–2: 37–44. https://doi.org/10.1080/17597269.2015.1045274

[13] Charlie Gilbert, Tzu-Chieh Tang, Wolfgang Ott, Brandon A. Dorr, William M. Shaw, George L. Sun, Timothy K. Lu, and Tom Ellis. 2021. Living materials with programmable functionalities grown from engineered microbial co-cultures. Nature Materials 20, 5: 691–700. https://doi.org/10.1038/s41563-020-00857-5

[14] David A. Gregory, Lakshmi Tripathi, Annabelle T.R. Fricker, Emmanuel Asare, Isabel Orlando, Vijayendran Raghavendran, and Ipsita Roy. 2021. Bacterial cellulose: A smart biomaterial with diverse applications. Materials Science and Engineering: R: Reports 145: 100623. https://doi.org/10.1016/j.mser.2021.100623

[15] Eduard Georges Groutars, Carmen Clarice Risseeuw, Colin Ingham, Raditijo Hamidjaja, Willemijn S. Elkhuizen, Sylvia C. Pont, and Elvin Karana. 2022. Flavorium: an Exploration of flavobacteria's living aesthetics for living color interfaces. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, 1–19. https://doi.org/10.1145/3491102.3517713

[16] Eduard Groutars, Raphael Kim, and Elvin Karana. 2024. Designing Living Artefacts for Multispecies Interactions: An Ecological Approach. International Journal of Design 18, 2.

[17] Juyeon Han, Euijin Shim, and Hye Rim Kim. 2019. Effects of cultivation, washing, and bleaching conditions on bacterial cellulose fabric production. Textile Research Journal 89, 6: 1094–1104. https://doi.org/10.1177/0040517518763989

[18] Yang Huang, Chunlin Zhu, Jiazhi Yang, Ying Nie, Chuntao Chen, and Dongping Sun. 2014. Recent advances in bacterial cellulose. Cellulose 21, 1: 1–30. https://doi.org/10.1007/s10570-013-0088-z

[19] M. Iguchi, S. Yamanaka, and A. Budhiono. 2000. Bacterial cellulose - a masterpiece of nature's arts. Journal of Materials Science 35, 2: 261–270. https://doi.org/10.1023/A:1004775229149

[20] Elvin Karana, Bahar Barati, Valentina Rognoli, and Anouk Zeeuw van der Laan. 2015. Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design 9, 2: 35–52.

[21] Elvin Karana, Bahareh Barati, and Elisa Giaccardi. 2020. Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts. International Journal of Design 14, 3: 37–53.

[22] Elvin Karana, Tom Ellis, Markus Linder, and Marie-Eve Aubin-Tam. 2023. Nextskins. Retrieved from: www.nextskins.eu.

[23] Elvin Karana, Holly McQuillan, Valentina Rognoli, and Elisa Giaccardi. 2023. Living Artefacts for Regenerative Ecologies. Research Directions: Biotechnology Design 1: e16. https://doi.org/10.1017/btd.2023.10

24. Raphael Kim, Pat Pataranutaporn, Jack Forman, Seung Ah Lee, Ingmar H. Riedel-Kruse, Mirela Alistar, Eldy S. Lazaro Vasquez, Katia Vega, Roland van Dierendonck, Gilad Gome, Oren Zuckerman, Angela Vujic, David S. Kong, Pattie Maes, Hiroshi Ishii, Misha Sra, and Stefan Poslad. 2021. Microbe-HCI: Introduction and Directions for Growth. In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems, 1–4. https://doi.org/10.1145/3411763.3450408

25. Raphael Kim, Clarice Risseeuw, Eduard Georges Groutars, and Elvin Karana. 2023. Surfacing livingness in microbial displays. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, 1–21. https://doi.org/10.1145/3544548.3581417

26. Suzanne Lee. 2024. BioCouture. Retrieved from http://xsead.cmu.edu/works/85.

27. Jue Li, Guiguang Chen, Ren Zhang, Hao Wu, Wei Zeng, and Zhiqun Liang. 2019. Production of high crystallinity type-I cellulose from Komagataeibacter hansenii JR-02 isolated from Kombucha tea. Biotechnology and Applied Biochemistry 66, 1: 108–118. https://doi.org/10.1002/bab.1703

28. Szu-Yu (Cyn) Liu, Jen Liu, Kristin Dew, Patrycja Zdziarska, Maya Livio, and Shaowen Bardzell. 2019. Exploring noticing as method in design research. In Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion, 377–380. https://doi.org/10.1145/3301019.3319995

29. Xingang Liu, Min Wu, Meng Wang, Qida Hu, Jingjing Liu, Yukun Duan, and Bin Liu. 2022. Direct Synthesis of Photosensitizable Bacterial Cellulose as Engineered Living Material for Skin Wound Repair. Advanced Materials 34, 13. https://doi.org/10.1002/adma.202109010

30. Qiuyu Lu, Andreea Danielescu, Vikram Iyer, Pedro Lopes, and Lining Yao. 2024. Ecological HCI: Reflection and Future. In Extended Abstracts of the CHI Conference on Human Factors in Computing Systems, 1–4. https://doi.org/10.1145/3613905.3643985

31. Malai ECO. 2025. Malai ECO. Retrieved from: https://malai.eco/.

32. Alan J. Marsh, Orla O'Sullivan, Colin Hill, R. Paul Ross, and Paul D. Cotter. 2014. Sequence-based analysis of the bacterial and fungal compositions of multiple kombucha (tea fungus) samples. Food Microbiology 38: 171–178. https://doi.org/10.1016/j.fm.2013.09.003

33. Holly McQuillan and Elvin Karana. 2023. Conformal, seamless, sustainable: Multimorphic textile-forms as a material-driven design approach for HCI. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, 1–19. https://doi.org/10.1145/3544548.3581156

REFERENCES

[34] Timothy Merritt, Foad Hamidi, Mirela Alistar, and Marta DeMenezes. 2020. Living Media Interfaces: A Multi-Perspective Analysis of Biological Materials for Interaction. Digital Creativity 31, 1: 1–21. https://doi.org/10.1080/14626268.2019.1707231

[35] Modern Synthesis. 2025. Modern Synthesis. retrieved from website: https://www.modernsynthesis.com/.

[36] Faranak Mohammadkazemi, Mehrdad Azin, and Alireza Ashori. 2015. Production of bacterial cellulose using different carbon sources and culture media. Carbohydrate Polymers 117: 518–523. https://doi.org/10.1016/j.carbpol.2014.10.008

[37] William Myers. 2012. Bio design: Nature, science, creativity. Thames & Hudson.

[38] Audrey Ng. 2017. Grown microbial 3D fiber art, Ava: Fusion of traditional art with technology. In Proceedings of the 2017 ACM International Symposium on Wearable Computers, 209–214. https://doi.org/10.1145/3123021.3123069

[39] Peter Q. Nguyen, Noémie-Manuelle Dorval Courchesne, Anna Duraj-Thatte, Pichet Praveschotinunt, and Neel S. Joshi. 2018. Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials. Advanced Materials 30, 19. https://doi.org/10.1002/adma.201704847

[40] Madalina Nicolae, Vivien Roussel, Marion Koelle, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2023. Biohybrid Devices: Prototyping Interactive Devices with Growable Materials. In Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology, 1–15. https://doi.org/10.1145/3586183.3606774

[41] Netta Ofer and Mirela Alistar. 2023. Felt experiences with kombucha scoby: Exploring first-person perspectives with living matter. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, 1–18. https://doi.org/10.1145/3544548.3581276

[42] Stefano Parisi, Valentina Rognoli, and Marieke Sonneveld. 2017. Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. The Design Journal 20, sup1: S1167–S1184. https://doi.org/10.1080/14606925.2017.1353059

[43] Pat Pataranutaporn, Angela Vujic, David S. Kong, Pattie Maes, and Misha Sra. 2020. Living Bits. In Proceedings of the Augmented Humans International Conference, 1–12. https://doi.org/10.1145/3384657.3384783

[44] Ana R. Rebelo, Andrew J. Archer, Xiuli Chen, Changqing Liu, Guang Yang, and Yang Liu. 2018. Dehydration of bacterial cellulose and the water content effects on its viscoelastic and electrochemical properties. Science and Technology of Advanced Materials 19, 1: 203–211. https://doi.org/10.1080/14686996.2018.1430981

[45] David Roedl, Shaowen Bardzell, and Jeffrey Bardzell. 2015. Sustainable Making? Balancing Optimism and Criticism in HCI Discourse. ACM Transactions on Computer-Human Interaction 22, 3: 1–27. https://doi.org/10.1145/2699742

45. Lucas Rosson, Boon Tan, Wayne Best, and Nolene Byrne. 2024. Applications of regenerated bacterial cellulose: a review. Cellulose 31, 17: 10165–10190. https://doi.org/10.1007/s10570-024-06220-0

46. Vivien Roussel, Marc Teyssier, Lucile Haute, and Pascal Dhulster. 2023. Processes, Fabrication and Design with Kombucha Bacterial Cellulose: Mapping Practices. Retrieved from https://www.researchgate.net/publication/373901304

47. F. Sederavičiūtė, P. Bekampienė, and J. Domskienė. 2019. Effect of pretreatment procedure on properties of Kombucha fermented bacterial cellulose membrane. Polymer Testing 78: 105941. https://doi.org/10.1016/j.polymertesting.2019.105941

48. Fernando Torres, Solene Commeaux, and Omar Troncoso. 2012. Biocompatibility of Bacterial Cellulose Based Biomaterials. Journal of Functional Biomaterials 3, 4: 864–878. https://doi.org/10.3390/jfb3040864

49. Sarah Webber, Ryan M. Kelly, Greg Wadley, and Wally Smith. 2023. Engaging with nature through technology: A scoping review of HCI research. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, 1–18. https://doi.org/10.1145/3544548.3581534

50. Rutger De Wit and Thierry Bouvier. 2006. 'Everything is everywhere, but the environment selects'; what did Baas Becking and Beijerinck really say? Environmental Microbiology 8, 4: 755–758. https://doi.org/10.1111/j.1462-2920.2006.01017.x

51. Jiwei Zhou, Bahareh Barati, Elisa Giaccardi, and Elvin Karana. 2022. Habitabilities of Living Artefacts: A Taxonomy of Digital Tools for Biodesign. International Journal of Design 16, 2: 57–73.

52. Jiwei Zhou, Raphael Kim, Zjenja Doubrovski, Joana Martins, Elisa Giaccardi, and Elvin Karana. 2023. Cyano-chromic interface: Aligning human-microbe temporalities towards noticing and attending to living artefacts. In Proceedings of the 2023 ACM Designing Interactive Systems Conference, 820–838. https://doi.org/10.1145/3563657.3596132

53. Katia Zolotovsky, Merav Gazit, and Christine Ortiz. 2018. Guided Growth of Bacterial Cellulose Biofilms. . 538–548. https://doi.org/10.1007/978-3-319-95972-6_58

[54] Katia Zolotovsky, Merav Gazit, and Christine Ortiz. 2018. Guided Growth of Bacterial Cellulose Biofilms. . 538–548. https://doi.org/10.1007/978-3-319-95972-6_58